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WATER HAMMER IN PIPELINES
CAUSED BY PERIODIC OPERATION
OF AN UPSTREAM VALVE

A THESIS

Presented to

The Faculty of the Graduate Division

by

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Approved:

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1962

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SUMMARY

In some mining operations ore is transported through pipelines in the form of a slurry. Occasional failure of pump casings indicates that very large transient pressures are sometimes generated in such systems. It has been observed that, in these systems, there is an apparent relationship between water hammer and cavitation in the pump nearest the pipeline intake. Such cavitation can be explained by clogging of the intake.

The purpose of this research was to study a type of unsteady flow in a pipeline which simulated periodic clogging and unclogging of material-transporting pipelines.

The model pipeline, consisting of three centrifugal pumps connected by copper tubing, was constructed so that the clogging-unclogging cycle could be simulated by periodic operation of a valve at the intake. Equipment was provided to make pressure measurements during both steady-flow and unsteady-flow tests.

Three runs of unsteady-flow tests were made. During these tests pressure-time records were made at three piezometers. During each of the three runs the inlet valve was opened and partially closed cyclicly, with a different amplitude of valve movement for each run.

Analysis of the pressure-time records yielded the following conclusions:

(1) Water-hammer waves originated from collapses of vapor pockets in successive pumps, beginning at an upstream pump; each wave was of greater magnitude than the previous one.

(2) The pressure rise in a particular pump and the time between collapses in successive pumps increased with increasing degree of cavitation in the pumps.

(3) Water-hammer waves were transmitted through operating centrifugal pumps under certain circumstances; when sufficiently large vapor pockets existed in the pumps the waves were reflected.

CHAPTER I

INTRODUCTION

Description of the Problem

This investigation is concerned with water hammer in pipelines containing cavitating pumps. The results of experiments performed on a laboratory model of a pipeline with three centrifugal pumps in series are analyzed.

In many mining operations a convenient method of transporting ore is to convey it through pipelines in the form of a slurry with centrifugal pumps providing the driving force. A common occurrence in material-transporting pipelines is the "blowing up" of pumps as if an explosion had taken place inside. In a report on exploratory tests Carstens (1) noted that observation indicated that the "blowing up" was related to the frequent operation of the upstream pump in a cavitating condition.

An explanation can be given for the cavitation in the upstream pump if the transported material is distributed unevenly throughout the slurry and clogs the intake. If the clogging of the suction line of the upstream pump results in cavitation at that pump, the head produced drops rapidly. This loss of head at the upstream pump can result in increasingly severe cavitation at each successive downstream pump, with the development of vapor cavities within those pumps. The pressure rise after termination of the clogging results in decay of the vapor cavities which, in turn, results in water hammer.

Purpose of the Research

The purpose of the research was to study experimentally a similar type of unsteady flow and the resulting pattern of unsteady pressure. The unsteady flow was caused by periodic operation of the inlet valve of a model pipeline containing three pumps in series. The periodic inlet-valve operation qualitatively resembles the clogging and unclogging of the material-transport pipeline. Three ranges of periodic valve operation were chosen so that the effect of differing degrees of pump cavitation would be incorporated into the experimental study.

Review of the Literature

The first important advances in the theory of water hammer were made by Joukovsky (2) and Allievi (3). With their works as a base others have made great strides in the application of theory to various types of design problems.

A number of investigators have concerned themselves with water hammer associated with water-column separation. Among these are Binnie (4), Binnie and Thackrah (5), Bunt (6), Apelt (7), Richards (8), and Kephart and Davis (9).

These writers considered column separation either downstream from a quickly closed valve or a pump that suddenly ceased operation, or at an elevated point in a pipeline. Heath (10) studied water hammer associated with column separation upstream from a valve caused by a negative reflected wave.

The only additional study of water hammer associated with cavitation in centrifugal pumps of which the writer has knowledge is a thesis by Martin (11). Martin's study was made with the same equipment used by the writer. The purpose was to study water hammer associated with a rapidly opened upstream valve. Martin was able to trace the origin of the water-hammer waves to the decay of vapor pockets within the pumps.

CHAPTER II

EQUIPMENT AND INSTRUMENTATION

General

The experimental investigation was performed on a laboratory model of a pipeline for which three centrifugal pumps in series provided the driving force. Piezometers were installed at various points along the length of the model. The equipment included instruments for measuring pressure at any given piezometer during steady-flow tests and instruments for making pressure-time records at three of the piezometers during unsteady-flow tests.

Arrangement of Pipeline Model

The general arrangement of experimental equipment is shown in Fig. 1*.

The model was submerged in water so that air leakage into the system at points of low pressure could be kept at a minimum. A wooden tank, which also acted as the reservoir for both intake and discharge, was used for this purpose.

The piping was copper tubing with an inside diameter of one-half inch. The sections of tubing were coiled so as

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*All tables and figures are shown in Appendix at end of thesis.

to fit in the tank.

A plug valve was placed at the intake of the pipeline. The degree of valve opening was indicated by a scale divided into ten units for the full range of movement.

Three Oberdorfer bronze centrifugal pumps, model 1G-P, were used in the pipeline. Each pump was driven by a one-third-horsepower, split-phase motor. The speed of rotation of the motors was 1750 revolutions per minute. By means of a system of pulleys and belts the pumps were operated at 5000 revolutions per minute. The drive shafts of the pumps extended through a sidewall of the tank. Leakage around the shafts was controlled by bushings.

The dimensions of the pipeline are shown in Fig. 2.

Instrumentation

Nine piezometers were provided for making pressure measurements. Piezometers were placed on the discharge and suction sides of the pumps and near the centers of the lengths of piping as shown in Fig. 2. These were connected to the pipeline by a tee. The piezometer tubes projected through the bottom of the tank and through the floor of the balcony on which the tank was located as shown in Fig. 3. The copper tubing for the piezometers was the same size as that used for the pipeline. Needle valves were connected to the ends of the piezometer tubes. The valves were submerged in buckets of water to reduce air leakage.

For the steady-flow tests the piezometers were connected to a single bourdon gage with flexible plastic tubing. The gage registered positive pressures in pounds per square inch, and pressure could be estimated to one-tenth of a pound per square inch. For negative pressures the gage registered in inches of mercury, and pressure could be estimated to one-tenth of an inch of mercury. Pressure was measured by opening the needle valve on a particular piezometer when all others were closed.

For the unsteady-flow tests pressure-time records were made with an oscillographic system consisting of pressure transducers and recorders. The needle valves on piezometers nos. 3, 6, and 9 were replaced by Statham electronic pressure transducers*. The transducers were connected to two Sanborn recorders with four-strand shielded cable. One recorder was connected to the transducer on piezometer no. 3 and the other to the transducers on piezometers nos. 6 and 9. Each recorder had an automatic timing device that made a mark on the recording paper at one-second intervals. By means of a remote switch and a relay, a mark was made simultaneously by the timing devices of both Sanborn recorders, thereby synchronizing the records.

Another series of unsteady-flow tests was recorded on an oscilloscope connected to the transducer on piezometer

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*The numbering system for pumps and piezometers is shown in Fig. 2.

no. 6. The oscilloscope was a DuMont cathode-ray type. The pressure fluctuations were recorded by making time photographs of the oscilloscope screen with a Polaroid camera.

CHAPTER III

PROCEDURE

Steady-Flow Tests with Downstream-Valve Control

The first tests were performed under steady-flow conditions. These tests were made to determine characteristics of the pumps with no cavitation and to determine the discharge in later tests by the slope of the piezometric head line. A globe valve was temporarily connected to the downstream end of the pipeline to maintain positive pressures in the system. Gravimetric measurements of discharge were made with one, two, and three pumps operating. Pressure measurements were made at all piezometers.

Steady-Flow Tests with Upstream-Valve Control

Steady-flow tests were made with upstream-valve control in order that the characteristics of the cavitating pumps could be determined. Pressure measurements were made for the full range of valve openings with all pumps operating.

Unsteady-Flow Tests with Oscillographic System

The unsteady-flow tests were made with the downstream valve removed and the pipeline discharging freely into the reservoir. The pressure fluctuations were measured at piezometers nos. 3, 6, and 9 by means of electronic pressure transducers connected to the recorders.

Unsteady flow was obtained by periodically opening and partially closing the upstream valve. In runs F, G, and H, the valve was operated between the limits of valve positions 2 and 6, 2 and 5, and 2 and 5½, respectively.

The oscillographic system was calibrated for pressure measurements by raising the ambient pressure in the pipeline a known amount by means of compressed air.

Unsteady-Flow Tests with Oscilloscope

These tests were made as a check on the response of the oscillographic system. All tests were made at piezometer no. 6 with the upstream valve operated periodically from valve position 2 to position 6. Time was measured by setting the speed of movement of the beam across the oscilloscope screen.

CHAPTER IV

SUMMARY AND DISCUSSION OF RESULTS

Summary of Steady-Flow Tests

The results of the steady-flow tests with downstream-valve control are shown in Table 1.

These results were used to define the approximate pump characteristic curves for the condition of no cavitation, shown as the upper curves in Fig. 4 (open circles).

The results of these tests were also used to determine a relationship between slope of the piezometric head line and weight rate of flow. This relationship permitted determination of the discharge in other steady-flow tests.

The Darcy-Weisbach equation and the Blasius equation for flow in smooth pipes can be combined and reduced to the form

$$s = K\ G^{1.75} \tag{1}$$

in which

s is the slope of the piezometric head line,

K is a constant,

G is the weight rate of flow (lb/sec).

Experimental solution was chosen for the constant in equation (1) because sufficiently accurate measurement of the diameter of the copper tubing was not considered feasible and because of additional losses that were introduced by dents in the tubing, the tubing being coiled, etc. However, since the maximum Reynolds number encountered in all tests was about 4×10^4, an equation of the Blasius type, (equation (1)), is applicable. The constant in equation (1) was found to have a value of 0.867.

Table 2 contains the results of the steady-flow tests with the upstream valve as the control.

The characteristic curves of the cavitating pumps derived from these tests are shown as the lower curves in Fig. 4 (closed circles).

The lines of pressure gradient (ordinate in pounds per square inch) are shown in Fig. 5 for the various valve positions.

The relationship between discharge and valve position in shown in Fig. 6.

Summary of Unsteady-Flow Tests

The results of the unsteady-flow tests will be discussed in the order of increasing amplitude of valve operation, that is, run G followed by run H and run F.

Typical sections of the pressure-time records made with the oscillographic system are shown in Figs. 7, 8, and

9, for runs G, H, and F, respectively. The range of valve operation in these respective runs was between the limits of valve positions 2 (fully open) and 5, 2 and 5½, and 2 and 6. The periods of the cycles of valve operation varied somewhat but were about 5.8, 5.0, and 5.9 seconds, for the three runs.

The waves of one cycle from each of runs G, H, and F, respectively, are shown at an enlarged scale in Figs. 10, 11, and 12. Also shown in Figs. 11 and 12, superimposed on the measured waves, are water hammer waves derived by a qualitative analysis of the problem.

The peak pressures at piezometers nos. 3, 6, and 9, for every cycle of operation are shown in Tables 3, 4, and 5, respectively.

Oscilloscopic records of pressure waves are shown in Fig. 13. The largest waves from the two photographs in Fig. 13 are shown at an expanded scale in Fig. 14. Also shown in comparison is the largest wave from Fig. 12, piezometer no. 6, and the corresponding wave derived by qualitative analysis.

Discussion of Steady-Flow Results

The upper curves of Fig. 4 are typical of centrifugal pumps operating without cavitation. Cavitation within a centrifugal pump is dependent on the pressure at the intake side. In this system the pressure at the pump intakes dropped with increased upstream valve closure, as is seen in Fig. 5. It is apparent that cavitation began to take effect in the pumps between valve positions 4 and 4½ (Fig. 4).

Different functions were used to define the discharge-valve position relationship of the pipeline for the conditions of cavitation and no cavitation (Fig. 6). It is observed in this Figure that the maximum discharge of the pipeline occurred at inlet-valve position 2. This demonstrates that the valve was fully open at position 2. Therefore, position 2 was one limit of valve movement for the periodic operation.

Discussion of Unsteady-Flow Results

General

It is apparent from Figs. 11 and 12 that pressures of water-hammer magnitude were generated in the pipeline by operation of the upstream valve. It is also apparent that these pressure surges were not generated in the classical manner by a rapidly closed downstream valve. The conclusion is drawn that water hammer resulted from water-column collision after some type of separation.

The most evident type of water-column separation in this experiment was vapor cavities formed within the pumps by cavitation, as indicated by pump characteristic curves (Fig. 4), by the lowest pressures in the pipeline existing at the intake sides of the pumps (Fig. 5), and by the noise characteristic of this type of phenomenon. Water hammer was then expected upon collapse of these vapor pockets as the result of the water-column collision. The recorded waves were analyzed in this light.

Discussion of Run G

The pressure fluctuations generated by the smallest amplitude of periodic valve operation are considered first.

As the upstream valve was closed from position 2 to position 5 the pressure in the pumps and throughout the pipeline decreased (Fig. 5). The pressure drop lagged the valve movement somewhat since steady flow is never established instantaneously upon change of conditions that control the flow. Therefore, it was concluded that, at the worst, the cavitation in pump no. 1, closest to the valve, was no more severe than for steady flow with the valve closed to position 5. In addition, it was concluded from Fig. 4 that the intensity of cavitation in pumps nos. 2 and 3 was less than in pump no. 1 for steady flow conditions. During unsteady-flow conditions the lag in flow establishment was expected to increase with distance from the point at which the flow was controlled, that is, the upstream valve. Therefore, the vapor cavities, if any, that developed in pumps nos. 2 and 3 were expected to be less extensive than those in pump no. 1.

It was believed that, upon valve opening, an elastic wave may have been formed by the collapse of vapor cavities in pump no. 1. If so, this was quickly dissipated because of the proximity of the pump to the intake. It was considered doubtful that large cavities developed in pumps nos. 2 and 3. Therefore, no elastic waves of appreciable magnitude were expected to originate in those pumps. The pressure surges shown in Fig. 10 were considered to be primarily of a dynamic nature associated with flow establishment.

Discussion of Runs H and F

What was concluded for run G does not apply to runs H and F.

Derivation of Equation for Pressure Rise. Consider the case of flow through a conduit in the vicinity of a pump in which a condition of column separation exists, such as operation with cavitation. If the pressure is increased at a point upstream from the vapor cavity then the liquid column will accelerate toward the cavity. Under these conditions the cavity will decrease in volume and eventually disappear. Upon complete collapse of the vapor cavity there will be a pressure rise, the magnitude of which will be primarily dependent upon the relative velocities of the water columns upstream and downstream from the previously existing cavity.

The pressure change across an elastic-wave front is formulated as follows (12)

$$\Delta p = -\rho c \, \Delta v \tag{2}$$

in which

Δp is the change in pressure across the wave front (lb/ft^2),

ρ is the mass density of the fluid ($lb\text{-}sec^2/ft^4$),

c is the celerity of an elastic wave in the given fluid (ft/sec),

Δv is the difference in velocity of the fluid columns upstream and downstream from the wave (ft/sec).

Immediately prior to collapse of the vapor cavity the approximate flow conditions upstream and downstream from the pump can be described as shown in Fig. 15 in which

v is the velocity downstream from the vapor cavity (ft/sec),

$v + \Delta v$ is the velocity upstream from the vapor cavity (ft/sec),

p is the pressure downstream from the vapor cavity (lb/ft^2),

p_v is the saturated vapor pressure of the fluid (lb/ft^2).

Saturated vapor pressure is a good first approximation of the pressure immediately upstream from the pump when a vapor pocket is present within.

When the cavity is collapsed the resulting elastic wave will move both upstream and downstream, that is, there will be two wave fronts. If the change in axial stress in the pipe wall is neglected, then, immediately after collapse, the conditions are approximately as described in Fig. 15 in which

v' is the velocity of the fluid between the two wave fronts (ft/sec),

Δp is the pressure rise of the water hammer wave (lb/ft^2).

Across wave I

$$\Delta p = -\rho c \, (v' - v - \Delta v)$$

Across wave II

$$\Delta p = -\rho c(-v' + v)$$

Adding

$$2\Delta p = -\rho c(-\Delta v)$$

$$\Delta p = \tfrac{1}{2}\rho c \, \Delta v \qquad (3)$$

<u>Qualitative Analysis of the Problem</u>. A partial understanding of the pattern of pressure waves recorded during this experiment was gained by studying a highly simplified analogous system and comparing the results with the pattern of pressure variation recorded in runs H and F.

In complex conduits an elastic wave is subject to a multiplicity of changes due to reflections, both positive and negative, partial transmission and partial reflection, etc. (13), in addition to viscous damping. Without great simplification, analysis of the pressure-time history in the experimental model would become so complex as to be unwieldy. However, this necessary simplification imposes definite limitations on the results derived. For this reason, it was not attempted in the analysis to predict the events that occur after the initial pressure rise at a pump drops back to the ambient pressure.

Consider a pipeline, such as illustrated in Fig. 16, in which there are three cavities, analogous to the pumps in the experimental model, equally spaced at a distance for which the travel time of an elastic wave is 0.02 second (equivalent to the experimental setup). Spaced intermediately between pumps and between pump and outlet are three piezometers numbered the same as the correspondents in the experimental model. The cavities (or pumps) are likewise numbered. Only the change of pressure from the ambient will be considered, that is, water-hammer waves and resulting reflections.

Figure 16 shows the events described in the following analysis.

As the upstream valve is opened the increase in pressure gradient initiates movement in the fluid upstream from pump no. 1 and the cavity is collapsed at time t_0. An elastic wave results.

In this case only, consideration will be given to the short length of pipe upstream from pump no. 1. After the pressure wave travels the short distance to the reservoir it is reflected negatively, that is, the pressure in the pipeline returns to a value equal to that of the reservoir (t_0 + 0.0005). Therefore, the duration of the pressure rise at any given point is about 1/2000 second, a time too rapid to be recorded by the oscillograph. Because of proximity to the pipeline intake, pump no. 1 will be considered to have no effect on the pressure fluctuations in the remaining analysis.

Upon collapse of the vapor cavity in pump no. 1 there is an immediate increase in the capability of the pump to impart energy to the fluid. The result of this is an increase in the pressure differential across the pump (the pressure differential changes from the lower to the upper curves in Fig. 4) and consequently an increase in the pressure gradient downstream from pump no. 1.

This increase in pressure gradient causes acceleration of the fluid and, ultimately, causes the vapor cavity in pump no. 2 to collapse (t_1). Pressure changes are recorded at piezometers nos. 3 and 6 simultaneously (t_1 + 0.01, t_1 + 0.03). This is based on the assumption that the wave front traveling downstream is reflected at the vapor pocket in pump no. 3, just as the wave traveling upstream is reflected at the reservoir. This seems to be a reasonable assumption based on the fact that the travel time of the pressure wave is short in comparison with the time required for decay of vapor pocket no. 3.

At time $t_1 + 0.04$ both waves, having been reflected negatively, meet at pump no. 2 and cause the pressure to be reduced by twice the magnitude of the initial pressure rise, less the effect of attenuation. As was previously stated, the continuous transmission and reflection of this wave throughout the pipeline will not be followed further because of the inadequacy of the simplified analysis to accurately predict a wave history.

At time t_2 the acceleration of the fluid causes the vapor pocket in pump no. 3 to collapse. This is deduced from the same reasoning which led to the prediction of the collapse of the vapor pocket in pump no. 2 at time t_1. Since the rate of flow is increasing with time during the process of flow establishment, the difference in velocity across pump no. 3, and therefore the consequent pressure rise, is expected to be greater than those which had obtained earlier across pumps nos. 1 and 2. Pressure changes are recorded at times $t_2 + 0.01$, $t_2 + 0.03$, and $t_2 + 0.05$. At time $t_2 + 0.06$ the pressure drops below the ambient and therefore the analysis is stopped.

<u>Comparison of Results of Qualitative Analysis with Recorded Waves</u>. The pressure fluctuations resulting from this analysis have been superimposed on the recorded waves in Figs. 11 and 12. The magnitude of the pressure was made

to conform, in general, with the measured pressure. Comparison of the results of the qualitative analysis with the recorded waves showed that the best agreement was provided by relating the results of the analysis to the peaks of the waves, rather than to the points of initiation of pressure rise. The waves have been shown in this manner in Figs. 11 and 12.

A number of observations can now be made about runs H and F in relation to the analytical solution.

It is observed (Figs. 11 and 12) that the recorded waves at piezometer no. 3 lagged those derived by analysis by about 0.04 second. This was possibly due to error in measurement. Pressure at piezometer no. 3 was recorded on a separate oscillograph, as was explained previously. The oscillographs were synchronized by simultaneous marks in the timer channel. Due to the relatively slow speed of the recorder paper (approximately 0.18 in/sec) a small error in the relationship of timer and pressure-measuring styli would cause a relatively large error in measurement. Additional error may have been introduced in reducing the data from the oscillograph records.

No water-hammer wave was attributable to pump no. 1 because of the short length of pipe from the reservoir to pump no. 1.

The first pressure fluctuations of appreciable magnitude occurred at piezometers nos. 3 and 6 at the same time (Figs. 11 and 12); they were not recorded at piezometer no. 9. It was therefore concluded that the waves originated in pump no. 2. Since the pressure at piezometer no. 9 remained at a relatively constant low value (about 2 lb/in^2 in run G, 2½ lb/in^2 in run F) indicative of cavitation in pump no. 3, the vapor pockets must have prevented the elastic waves from being transmitted through that pump.

It was noted that the results of the qualitative analysis agreed with the measured results insofar as the first wave originated in pump no. 2. However, there was no similarity in shape, that is, the pressure-time relationships were quite dissimilar. This result was expected when an explanation was given for not carrying the analysis out beyond the first wave. In the pipeline model there were waves reflected from piezometers, from changes in elasticity in the piping, from pumps, from reservoirs, etc., that traveled throughout the system until attenuated by viscous forces. It was these waves that were difficult to predict.

The next wave is observed to reach a peak simultaneously at piezometers nos. 6 and 9 (Figs. 11 and 12). This indicates that the source of the wave was pump no. 3, which was situated midway between the piezometers. The later occurrence of a wave recorded only at piezometer no. 3 indicates that this was the same wave and that it had been transmitted through pump no. 2.

It was noted that the wave emanating from pump no. 3 was of greater magnitude than previous waves. This conforms with the assumptions made earlier. Whereas the velocity downstream from a pump did not vary greatly prior to collapse of vapor cavities, the upstream velocity increased during the process of flow establishment.

Again the pressure-time relationship (shape) of the recorded wave did not agree with the results of the qualitative analysis. This will be discussed further in the following section.

This study indicated that a wave was transmitted through a pump under certain circumstances (wave originating in pump no. 3 transmitted through pump no. 2) but when a vapor pocket of sufficient magnitude was present (pump no. 3) the wave was reflected (wave originating in pump no. 2). The relationship between the severity of cavitation and the reflection and transmission characteristics of a centrifugal pump was not known and could not be determined from the results of this experiment.

Also evident was the change in time between the first and second waves. In terms of the qualitative analysis, $t_2 - t_1$ was greater in run F than in run H. Since the time required to establish flow sufficient to collapse the vapor cavities in a pump is dependent on the size of the cavities present, the time, $t_2 - t_1$, was expected to increase with increased range of valve operation.

Pressure-Time History of Wave from Oscilloscope. The magnitude and shape (pressure-time at a given point) of a water-hammer wave caused by water-column collision with a boundary, such as a valve, can be predicted with a very good degree of reliability (10). Not so much is known, however, when the water-column collision occurs at some interior point in a pipeline. Even less is known about the wave forms to be expected when a vapor pocket collapse occurs in an operating pump. In the qualitative analysis it was assumed that there was an instantaneous pressure rise to the theoretical value, which is certainly not valid. The complexity of the problem has been suggested by Kephart and Davis (14).

> ...the authors suspect that steam formed during a water column separation does not condense at constant pressure as has been customarily assumed heretofore in calculations of this type. The manner in which dissolved gases leave and re-enter solution may be of significance. The formation of a single discreet vapor-air bubble with a true interfacial separation seems highly improbable; it appears more likely that an air-vapor-liquid mixture of relatively long length is formed. Generation of surge pressure upon collapse of a foamy mixture may bear little relationship to surge pressure generated by collapse of a discreet air-vapor space.

Some indication of the pressure-time relationship of the waves generated under certain conditions is given by Fig. 13. These are photographs of pressure fluctuations at piezometer no. 6 recorded by an oscilloscope for the condition of the upstream valve being operated cyclicly from positions 2 to 6. The largest waves in the two photographs are shown together at an expanded scale in Fig. 14. Also shown in this Figure is the equivalent wave from Fig. 12 (piezometer no. 6, run F) and the corresponding wave derived by qualitative analysis.

The lack of agreement is quite obvious. This indicates that the oscillograph was not sensitive enough to follow the rapid changes in pressure but did seem to record the correct order of magnitude. When the nearly vertical lines of the largest waves in Fig. 9 were compared with one of the same waves plotted in Fig. 14 it was realized that the slow speed at which the recordings were made on the oscillograph certainly must have contributed to the inaccuracy. Figure 14 shows that the results from the oscillograph are probably of too long a duration and that the true duration was closer to the proposed analytical solution. The relation of the recorded wave and the actual time of the water-hammer surge could not be determined.

Comparison of Change of Range of Valve Operation in the Three Runs

Tables 3, 4, and 5 show the resultant maximum pressure on each cycle of operation at piezometers nos. 3, 6, and 9, respectively, for each run. Because the upstream valve was operated manually differences in period and other dissimilarities are involved. Therefore, to make any sort of statistical analysis of the few cycles of operation recorded would have been misleading. Nevertheless, certain observations were made.

The trend was quite evident. The maximum pressure at the various piezometers increased with increasing amplitude of valve operation.

Figures 4 and 5 show that the cavitation in all pumps increased with decreasing inlet valve opening. It was intuitively reasoned therefore that the size of the vapor pockets in the pumps increased under the same conditions. For this reason a longer time to collapse each pocket was required as the range of valve operation increased. This, then, permitted a larger upstream velocity to be attained before collapse and therefore a larger maximum pressure resulted.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Due to the exploratory nature of this experiment the conclusions drawn are not necessarily general in nature. However, it is believed that they give some insight into the phenomena inherent in problems of water hammer related to pump cavitation.

The conclusions drawn from this study are as follows:

(1) Water-hammer pressures could be generated in a pipeline system containing centrifugal pumps in which there were unsteady-flow conditions.

(2) During that phase of unsteady operation in which the flow was accelerating, water-hammer waves originated from collapses of vapor cavities in successive pumps, beginning at an upstream pump.

(3) The pressure rise of the water-hammer waves increased with successive collapses, as the velocity of flow increased.

(4) The pressure rise of the water-hammer waves increased with increasing degree of cavitation in the pumps.

(5) The time between vapor-cavity collapses in consecutive pumps increased with increasing degree of cavitation in the pumps.

(6) Water-hammer waves were transmitted through operating centrifugal pumps in which there was no cavitation but were not transmitted through those same pumps when vapor pockets of sufficient size were present.

Recommendations

The following recommendations are made to future investigators:

(1) Study should be made of the relationship between velocity of flow upstream and downstream from a vapor pocket in a pump and the pressure rise resulting from its collapse.

(2) Study should be made of the effect of differing degrees of cavitation on the pressure-time relationship of the water-hammer waves resulting from collapses of vapor cavities in centrifugal pumps.

(3) The transmission-reflection characteristics of water-hammer waves passing through operating centrifugal pumps should be studied in relation to the degree of cavitation in the pumps.

APPENDIX

On the following pages appear the tables and illustrations of this thesis.

Table 1. Data from Steady-Flow Tests with Downstream-Valve Control

Gage Pressure in Pipeline (lb/in^2)

Pumps Operating	Piezometer Number 1	2	3	4	5	6	7	8	9	Flow Rate (lb/sec)
1, 2, 3	-2.1	18.9	11.5	3.5	24.7	17.4	8.9	31.8	22.8	0.660
1, 2	-1.2	21.0	16.0	10.5	33.2	28.1	22.4	21.0	14.9	0.532
1	-0.4	23.0	20.2	17.3	16.7	13.9	10.8	10.1	6.9	0.377
1	0.4	27.0	-	-	-	-	-	-	-	0
2	-	-	-	0.3	26.6	-	-	-	-	0
3	-	-	-	-	-	-	0.3	28.3	-	0

Table 2. Data from Steady-Flow Tests with Upstream-Valve Control

Gage Pressure in Pipeline (lb/in^2)

Valve Position	Piezometer Number 1	2	4	5	7	8	9	Flow Rate (lb/sec)
0	-4.9	17.1	-2.5	19.6	-1.0	21.8	10.4	0.765
1	-1.6	19.7	-0.6	21.3	0.3	22.5	10.8	0.777
2	-0.9	20.4	-0.1	21.8	0.5	22.7	10.9	0.780
3	-2.1	19.3	-1.1	20.8	0	22.2	10.7	0.774
4	-6.3	15.0	-3.8	18.1	-1.4	21.0	10.2	0.743
4½	-10.4	9.9	-6.7	13.5	-3.6	17.9	8.8	0.684
5	-11.6	-0.3	-10.7	3.8	-6.5	11.6	5.5	0.526
5½	-12.4	-5.1	-11.2	-1.4	-8.0	6.7	3.5	0.385
6	-12.8	-8.8	-11.9	-4.5	-8.1	3.8	1.8	0.278
7	-12.1	-11.4	-12.1	-6.4	-6.7	1.3	0.8	0.102
* 8	-12.1	-12.1	-12.7	-7.7	-9.2	0.9	0.6	--
9	-12.9	-12.9	-12.8	-12.1	-12.0	0.6	0.3	0

* Pulsating flow was present at this valve position.

Table 3. Maximum Pressure per Cycle at Piezometer No. 3

Wave	Run G	Run H	Run F
1	14.8	42.2	48.1
2	9.7	32.3	54.5
3	13.8	57.1	47.7
4	13.7	24.5	39.4
5	14.1	34.7	37.8
6	13.8	21.3	47.1
7	14.6	22.0	46.4
8	16.9	20.4	33.6
9	13.6	20.4	19.6
10	11.7	24.3	39.0
11	11.0	33.5	43.6
12	--	38.7	42.0
13	--	22.5	21.3
14	--	32.1	42.1
15	--	24.5	41.2
16	--	30.6	44.2
17	--	41.4	48.1
18	--	30.3	51.5

Table 4. Maximum Pressure per Cycle at Piezometer No. 6

Wave	Run G	Run H	Run F
1	24.0	53.0	103.8
2	13.1	38.2	88.1
3	17.9	78.8	102.2
4	20.2	24.4	83.1
5	21.8	39.9	66.2
6	19.8	34.6	72.0
7	22.7	19.4	64.9
8	22.5	27.4	45.6
9	22.0	27.4	25.6
10	19.8	30.0	57.9
11	18.6	49.5	64.8
12	--	43.7	47.2
13	--	28.8	33.4
14	--	42.1	67.9
15	--	23.2	65.7
16	--	38.2	57.8
17	--	58.1	59.9
18	--	40.0	61.3

Table 5. Maximum Pressure per Cycle at Piezometer No. 9

Wave	Run G	Run H	Run F
1	18.4	44.9	105.9
2	12.4	28.4	111.3
3	14.9	43.3	114.1
4	16.8	19.8	76.6
5	16.2	29.5	56.3
6	16.4	20.3	54.5
7	16.7	19.5	44.1
8	17.5	22.1	33.5
9	18.8	21.8	23.7
10	16.3	25.3	37.1
11	15.9	30.5	50.9
12	--	34.3	45.7
13	--	18.9	32.1
14	--	34.0	65.2
15	--	21.4	49.7
16	--	31.2	65.0
17	--	41.3	70.3
18	--	29.9	49.7

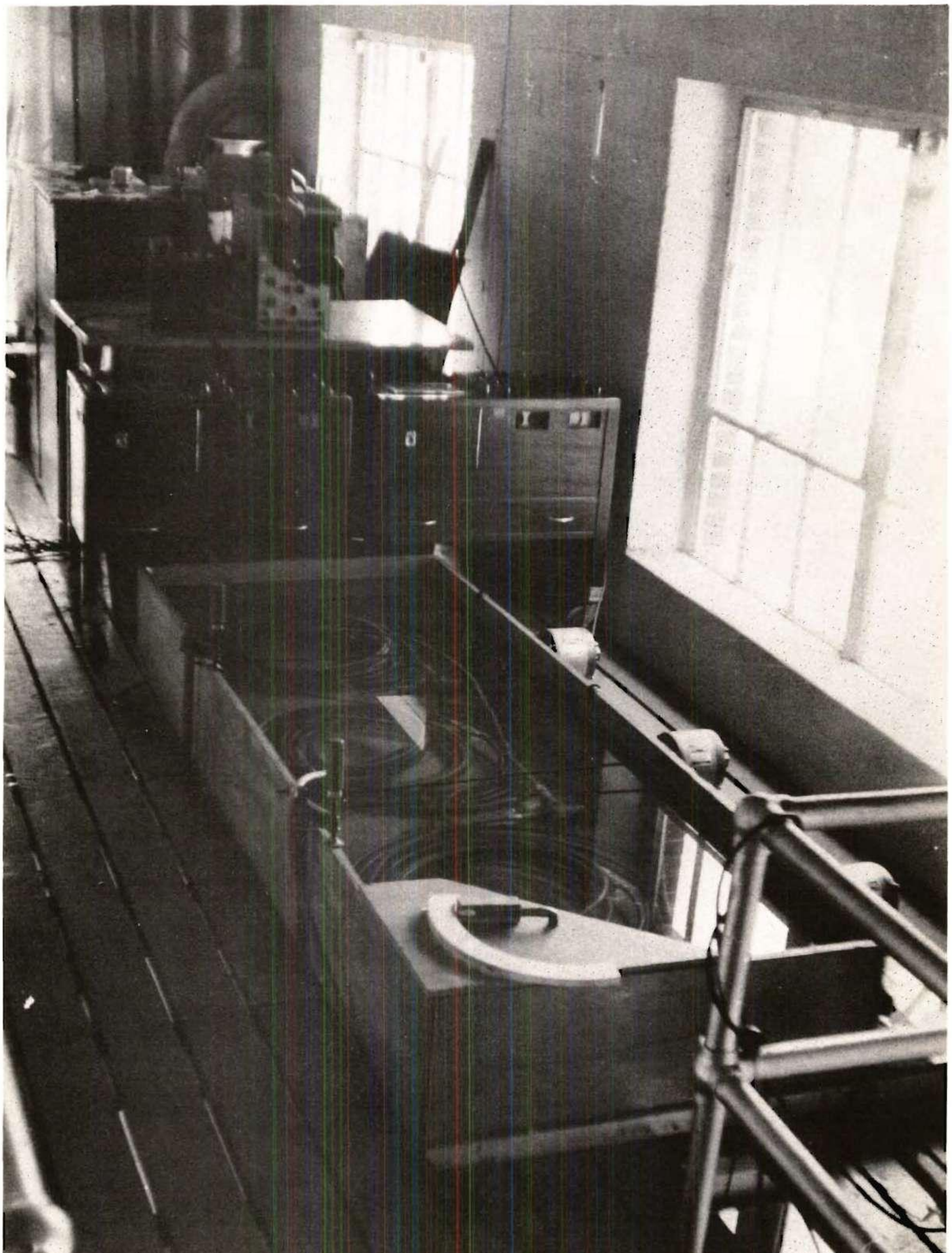


Figure 1. View of Laboratory Equipment

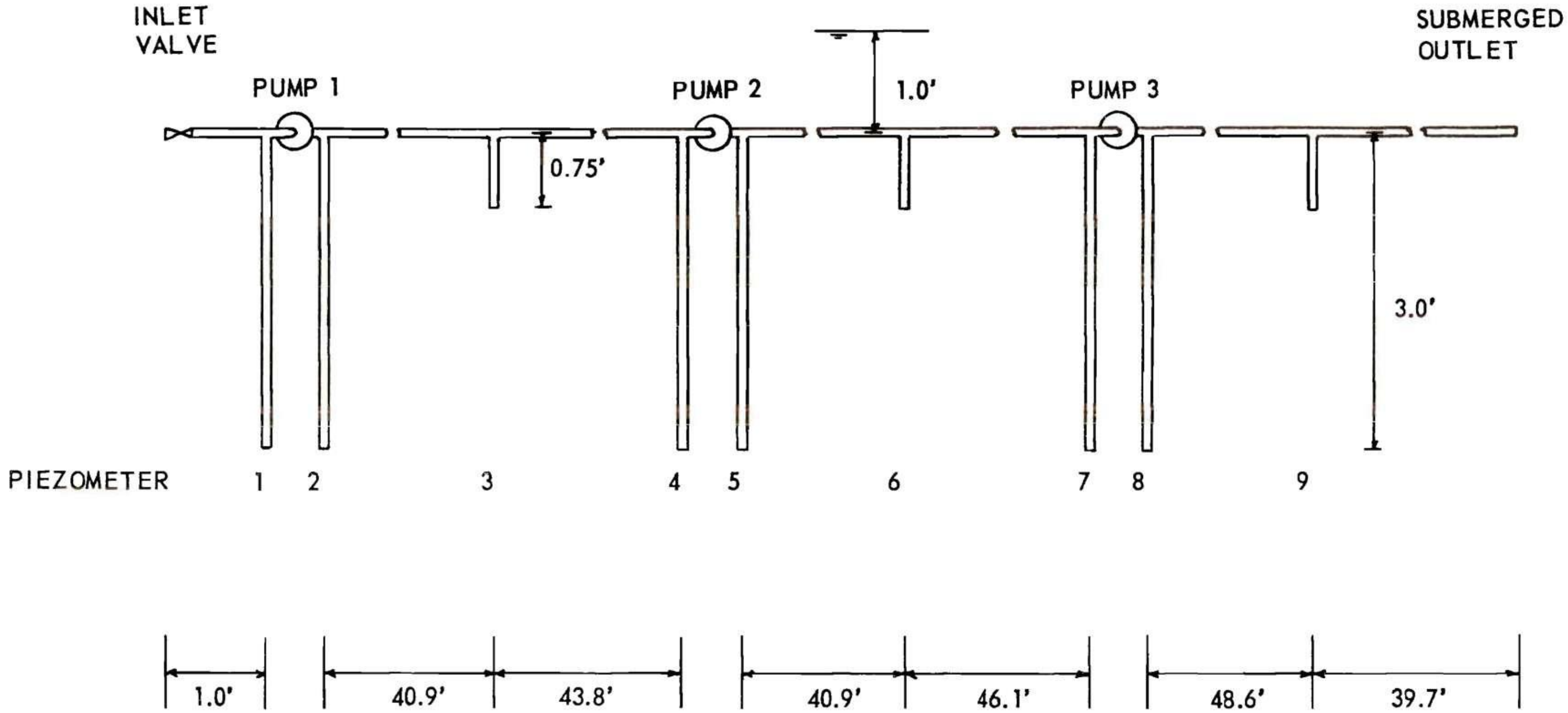


Figure 2. Dimensions of Pipeline

Figure 3. View of Piezometers and Pressure Transducers

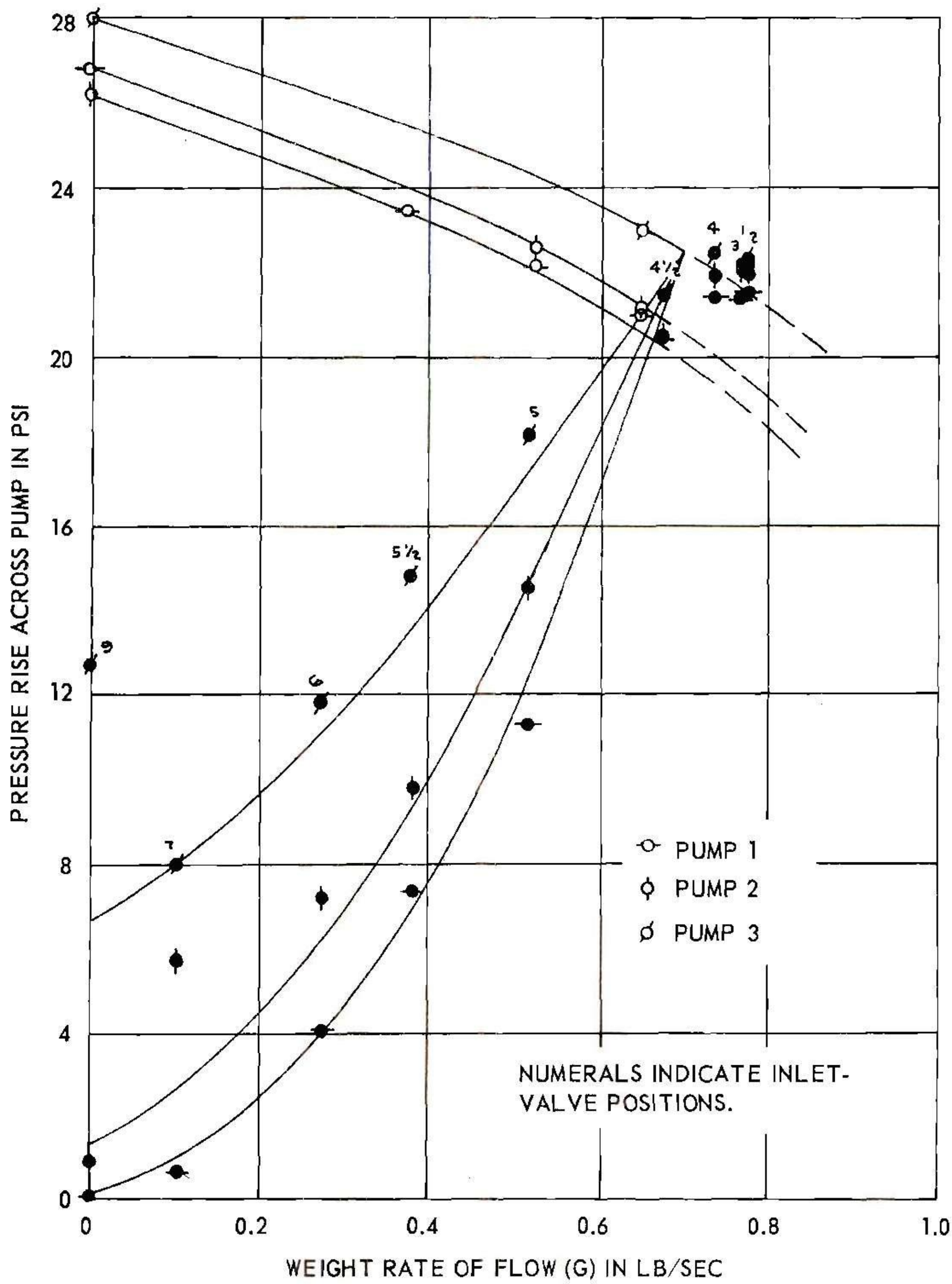


Figure 4. Pump Performance Characteristics

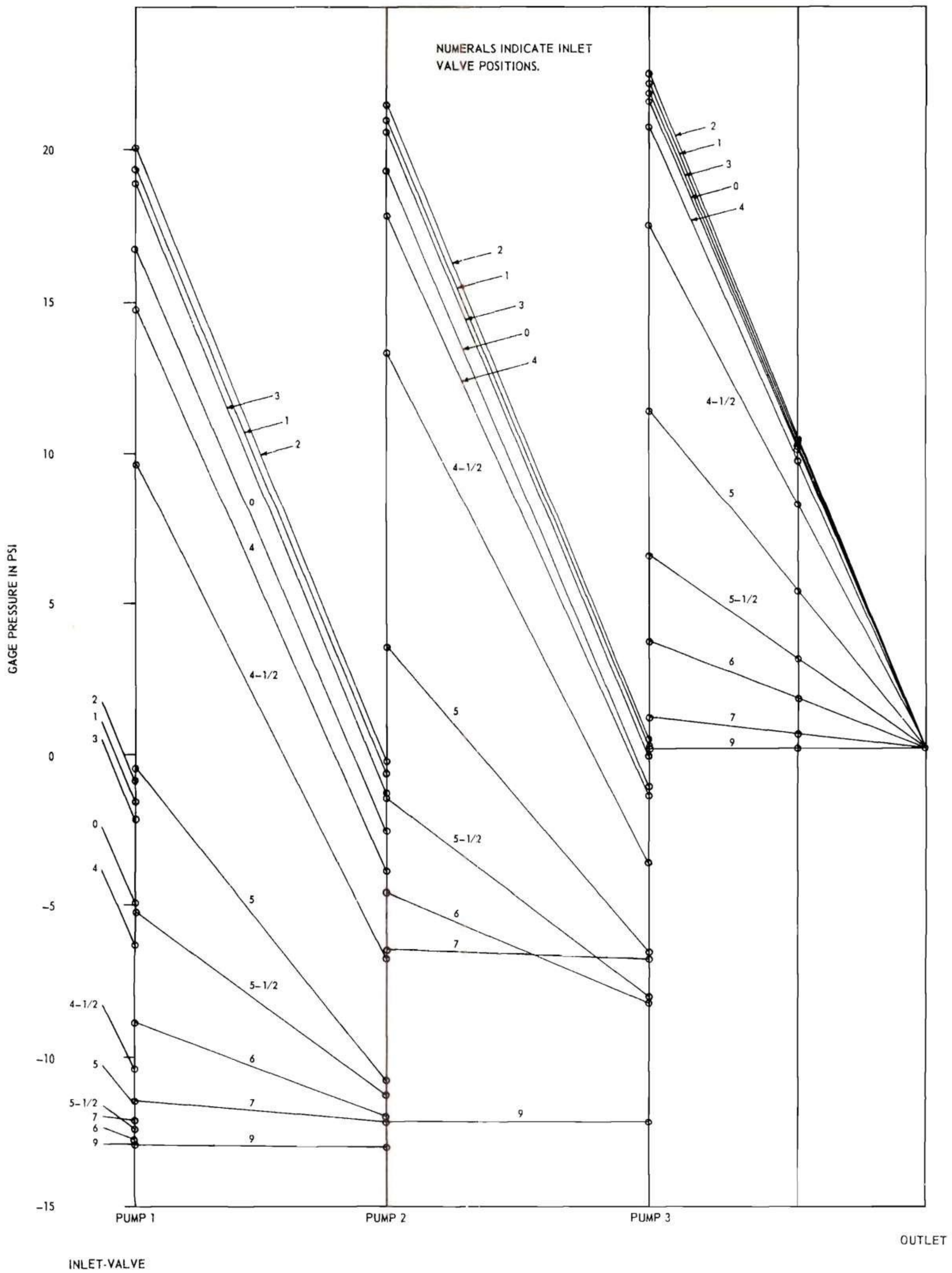


Figure 5. Pressure Gradient Lines for Various Valve Positions

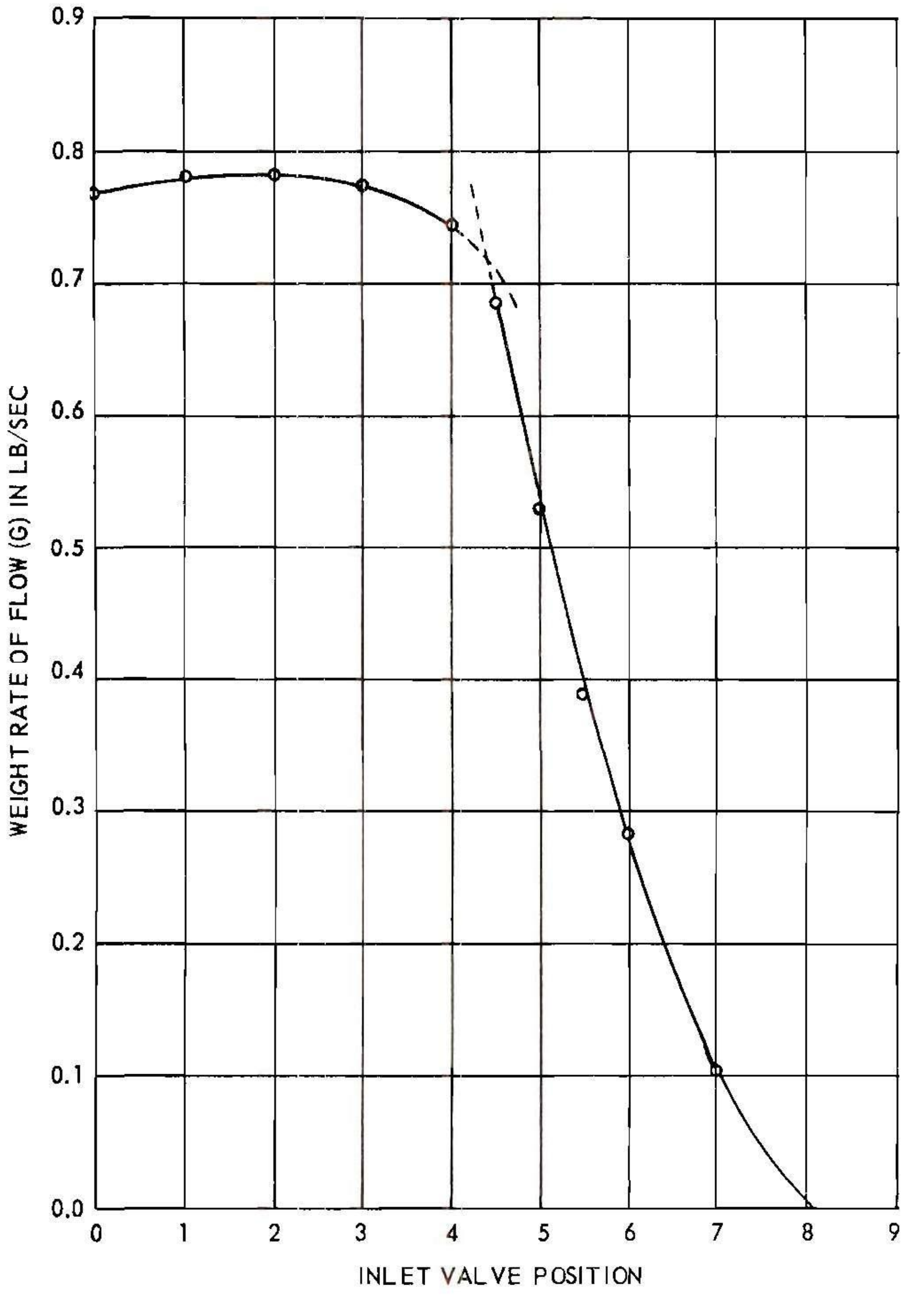


Figure 6. Relationship between Discharge and Valve Position

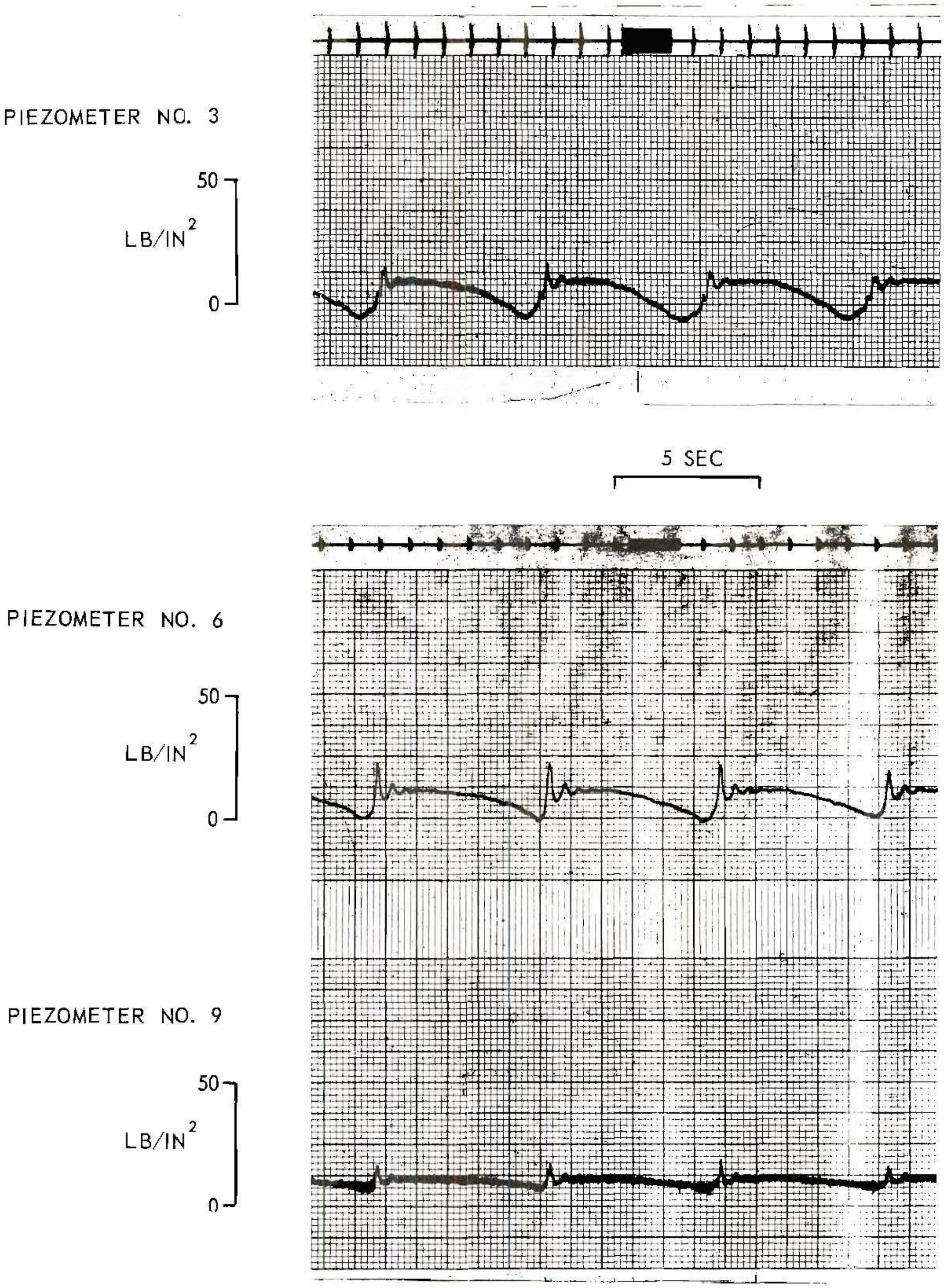


Figure 7. Typical Section of Oscillographic Record--Run G

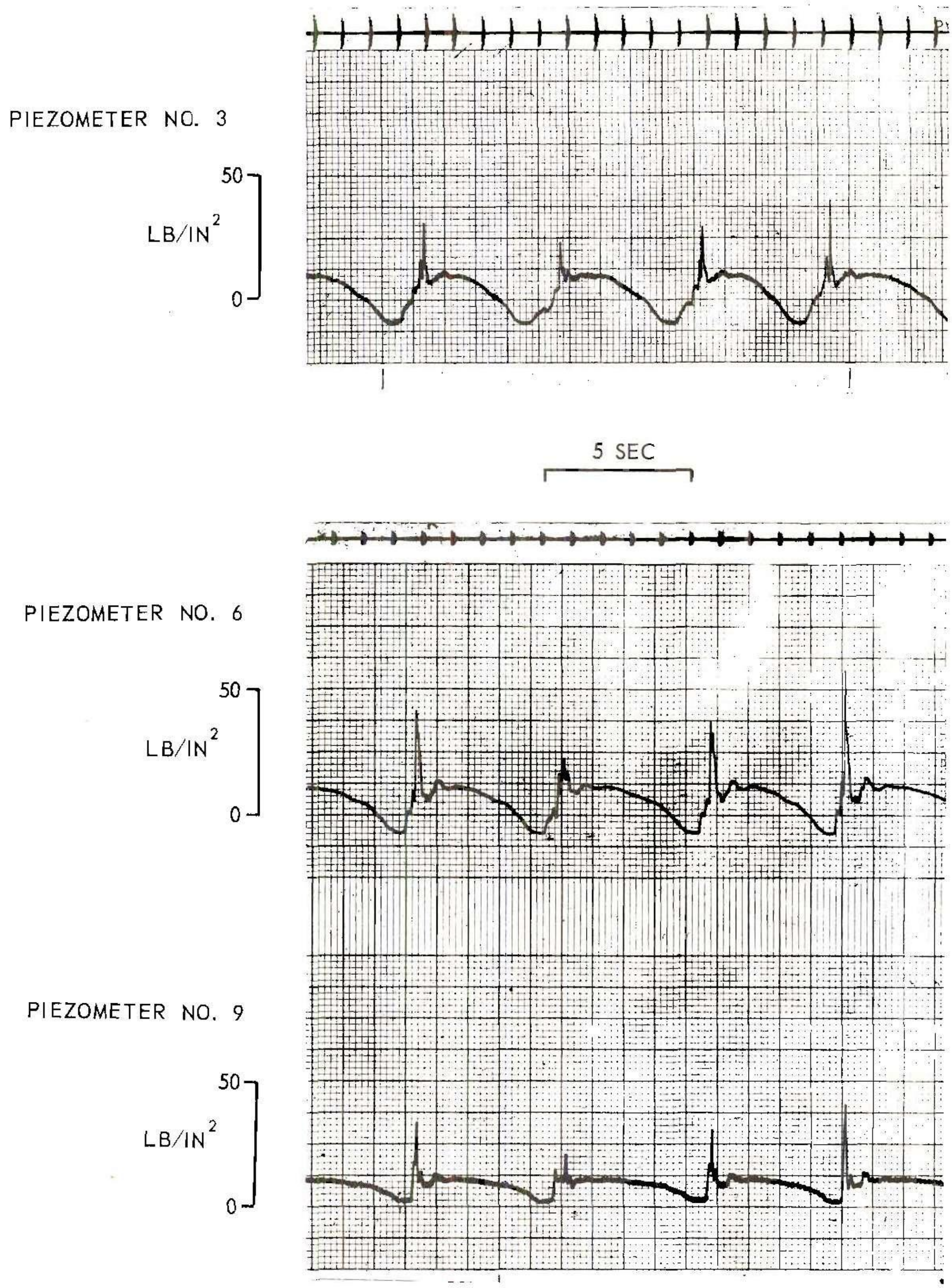


Figure 8. Typical Section of Oscillographic Record--Run H

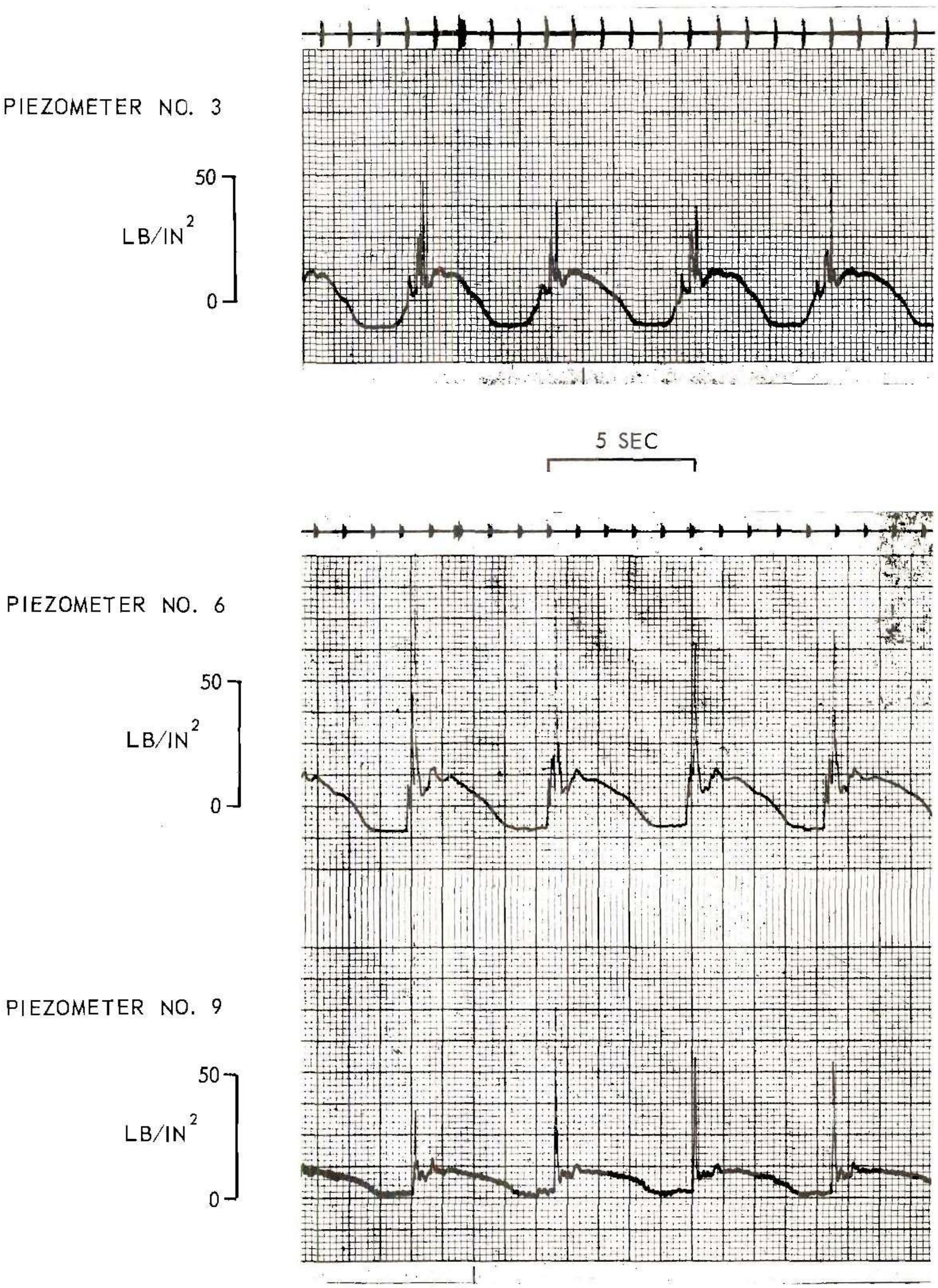


Figure 9. Typical Section of Oscillographic Record--Run F

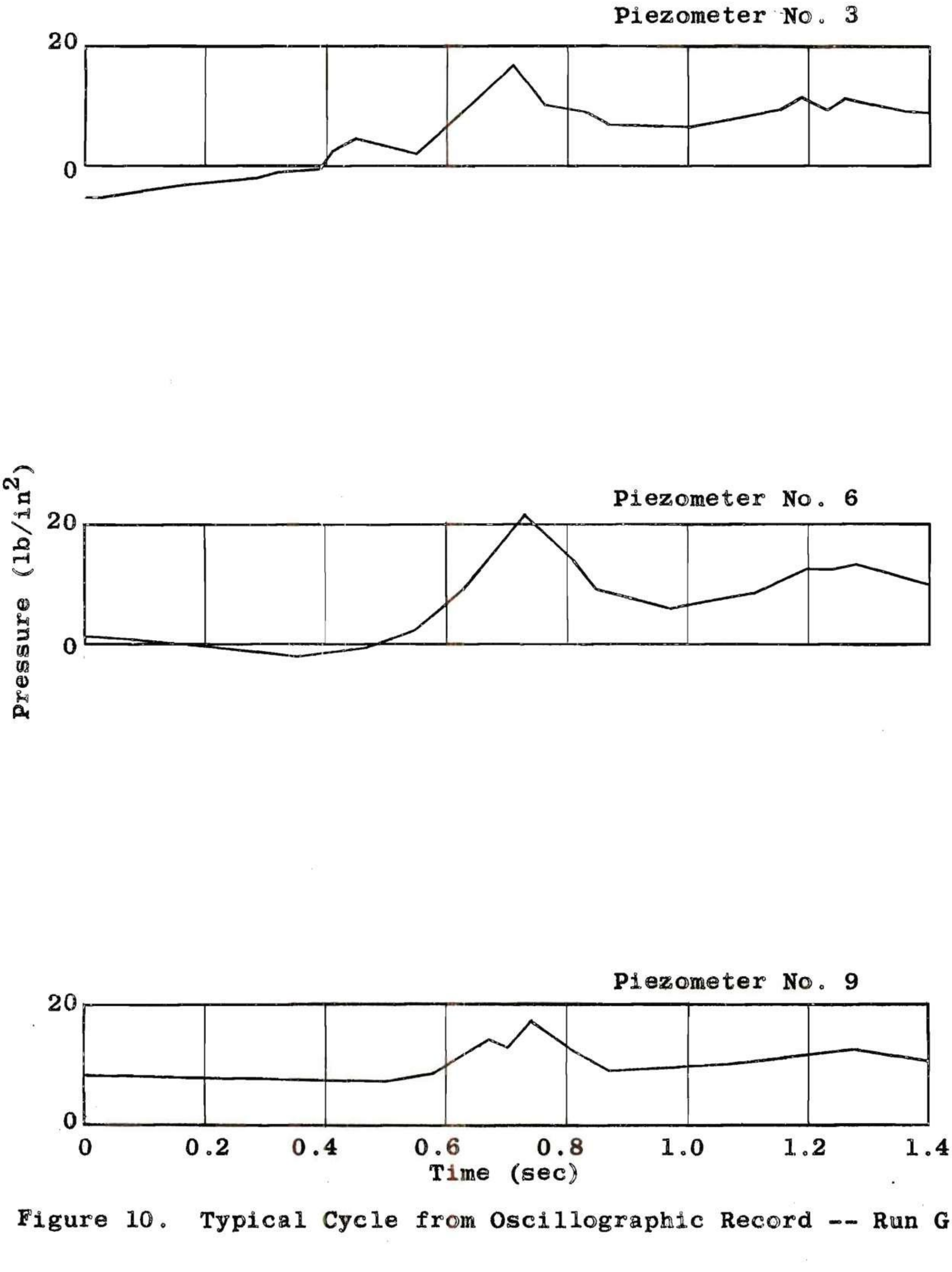


Figure 10. Typical Cycle from Oscillographic Record -- Run G

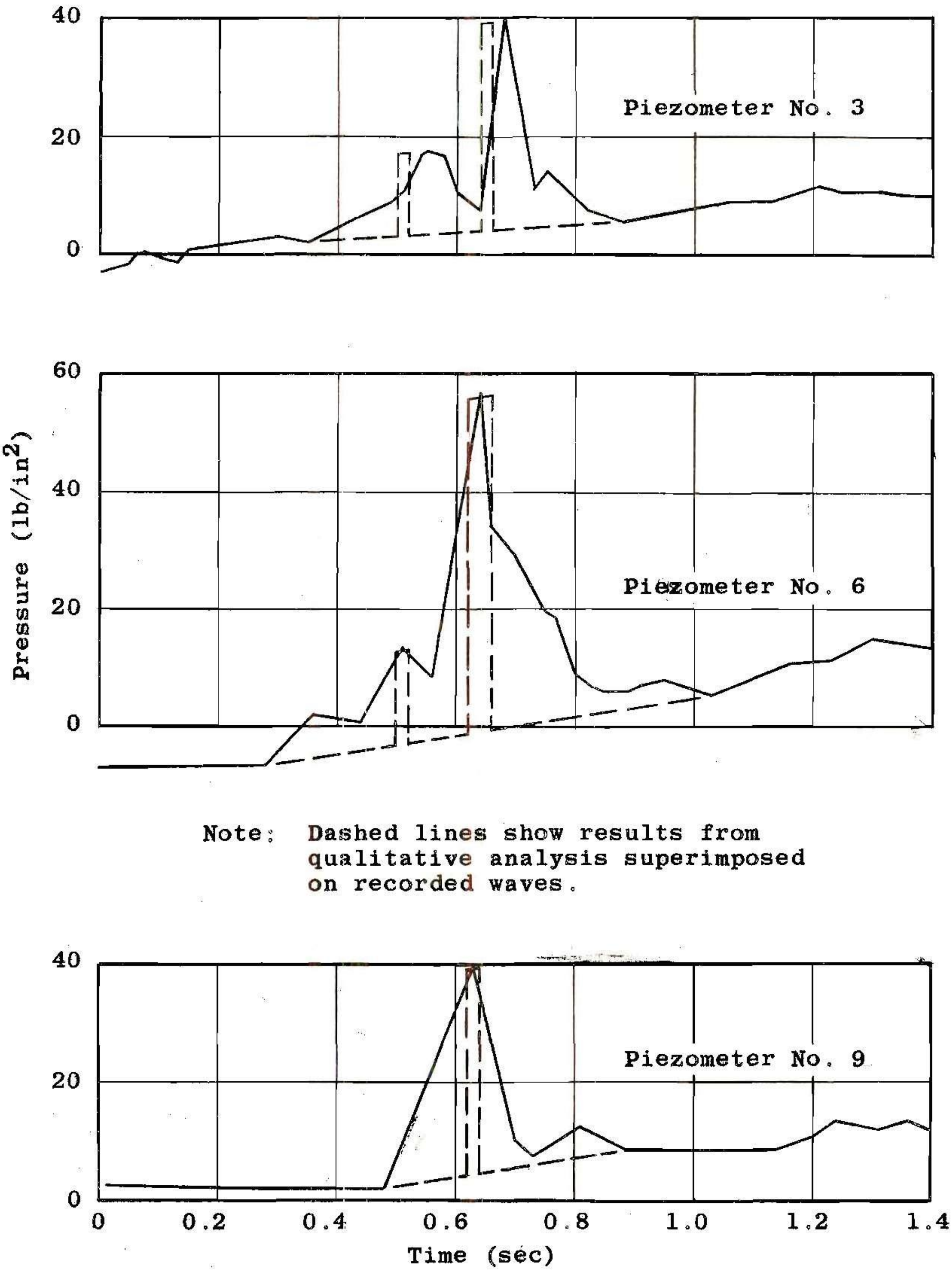


Figure 11. Typical Cycle from Oscillographic Record -- Run H

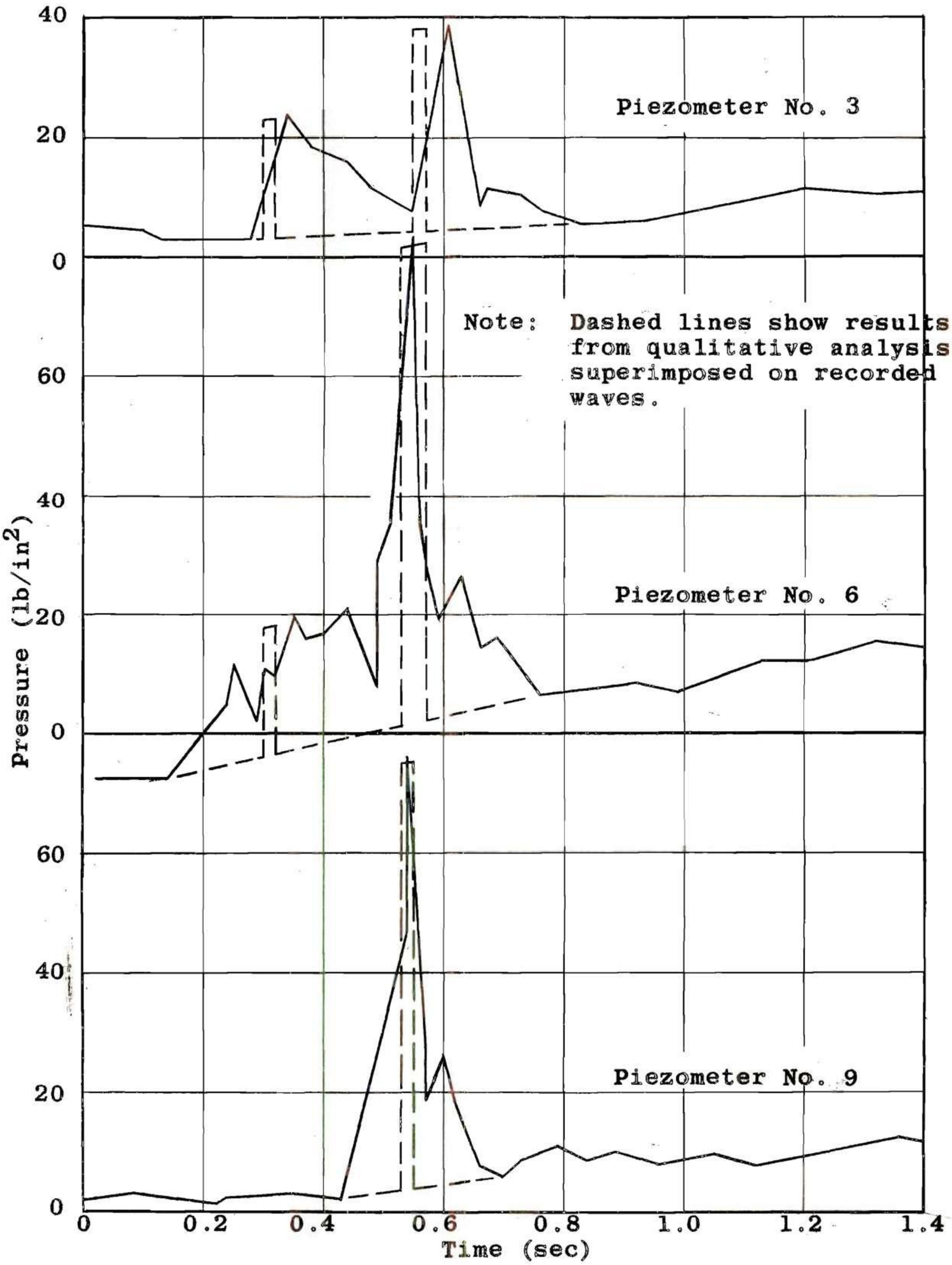
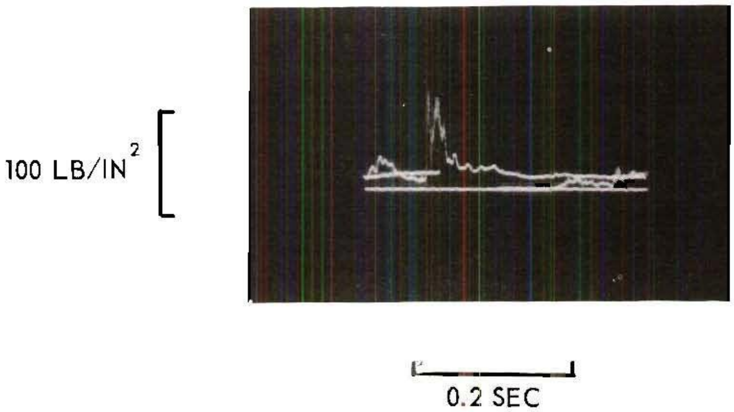


Figure 12. Typical Cycle from Oscillographic Record -- Run F



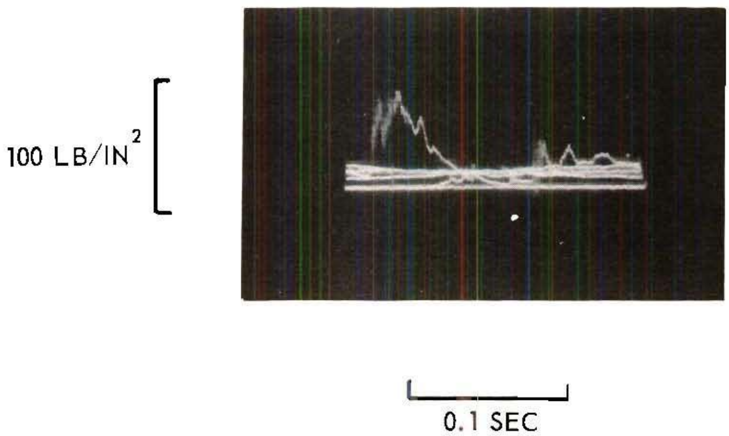


Figure 13. Typical Oscilloscopic Records

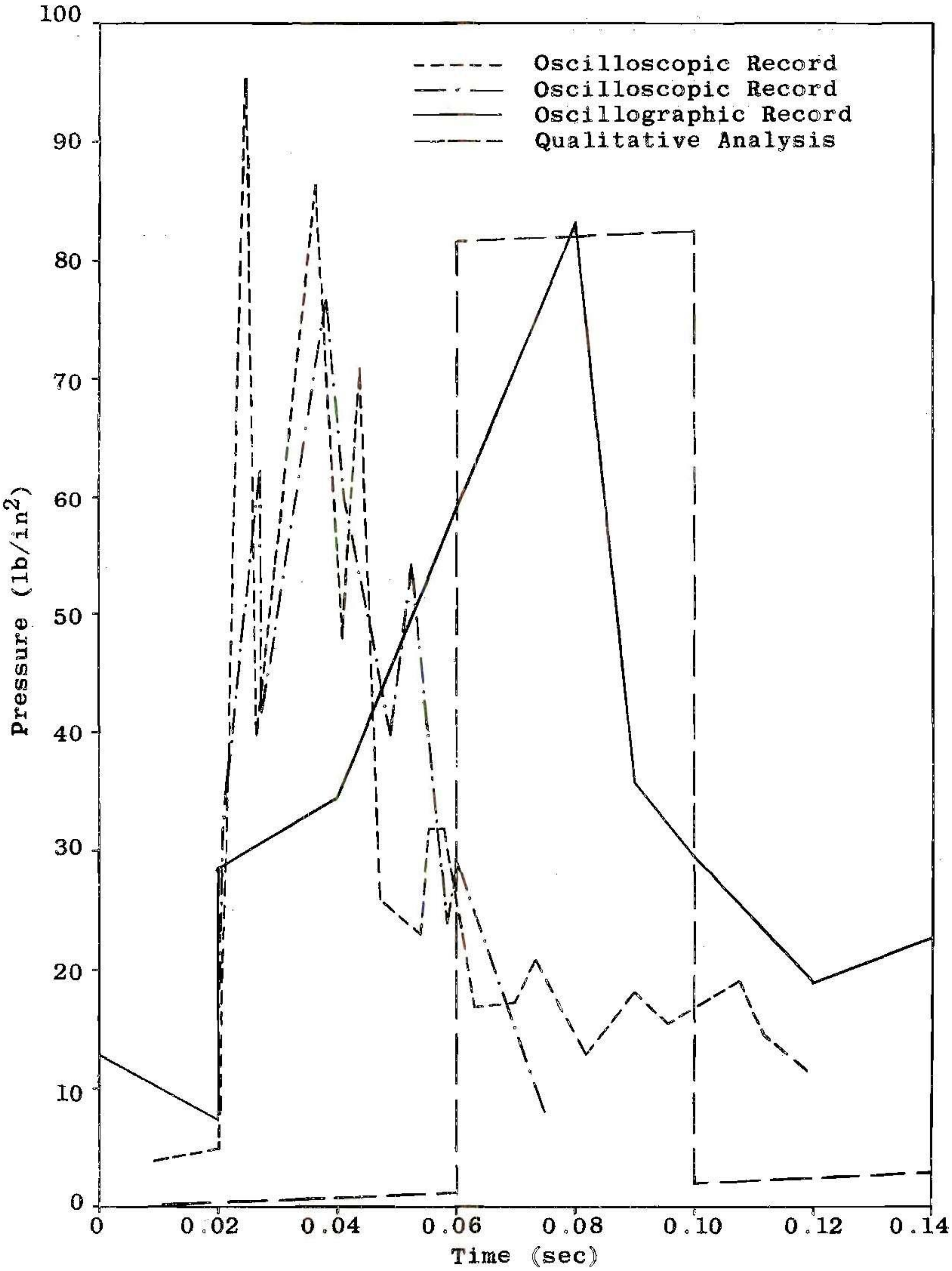
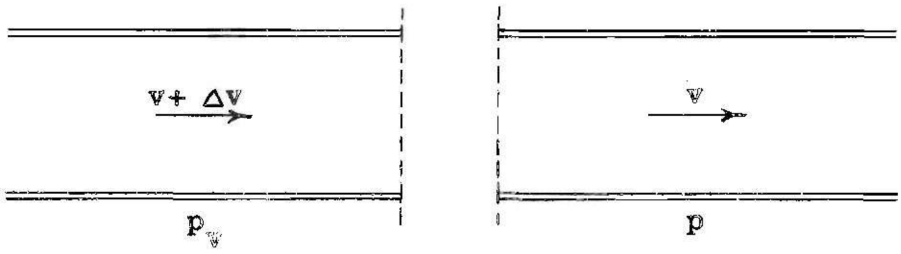
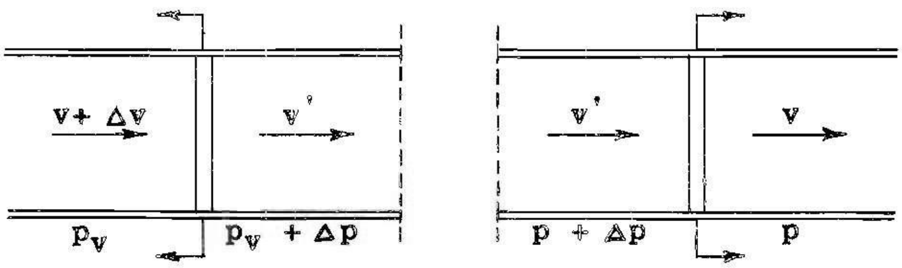


Figure 14. Pressure-Time History of Largest Wave at Piezometer No. 6



a. Prior to Water-Column Collision



b. Subsequent to Water-Column Collision

Figure 15. Approximate Flow Conditions Upstream and Downstream from a Pump Prior to and Subsequent to Water-Column Collision

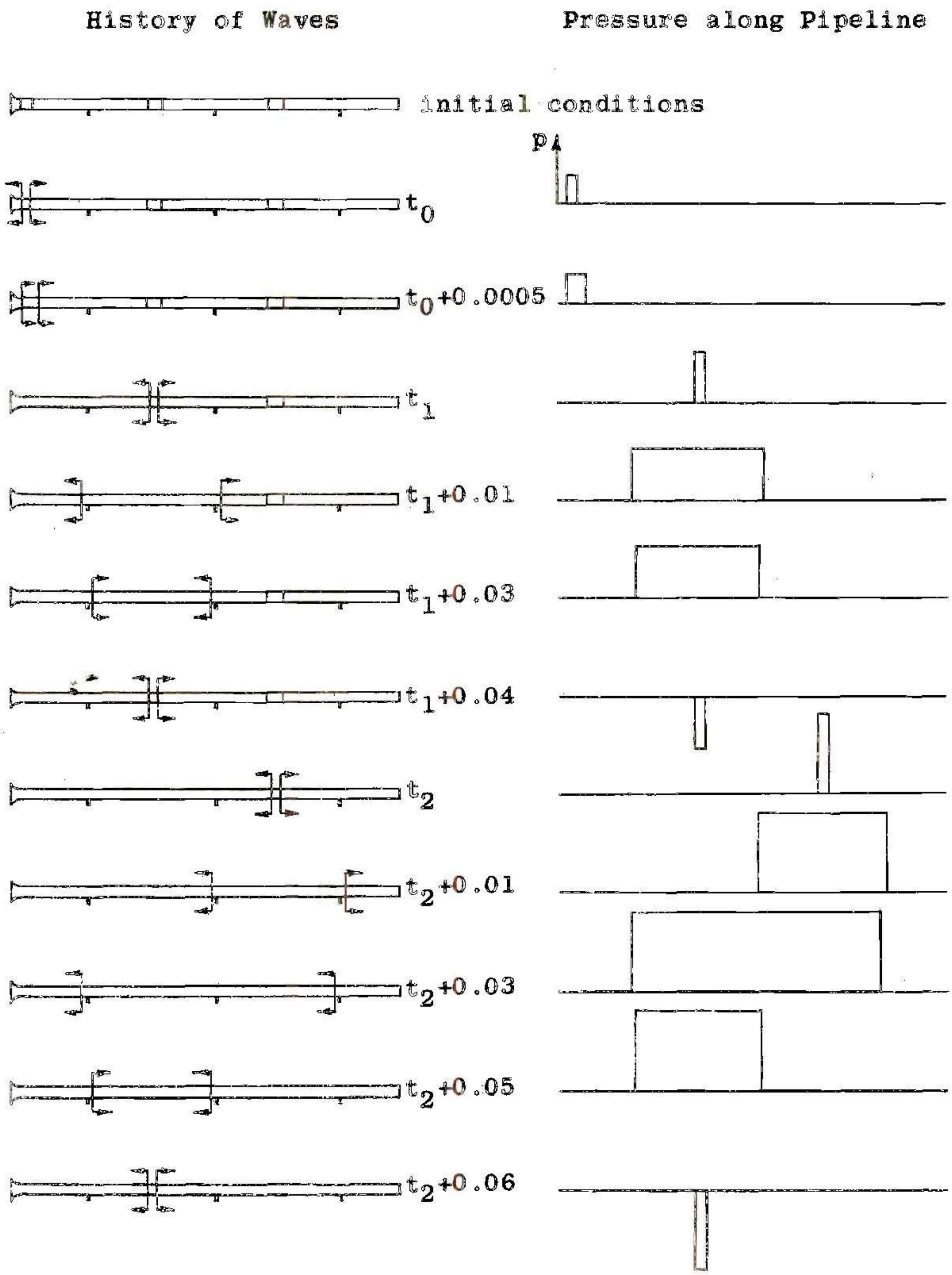


Figure 16. History of Water-Hammer Waves in Qualitative Analysis

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13. Ibid., pp. 479-483.

14. Kephart and Davis, op cit., p. 460.